"Efficient Simulation of Coupled Ground Antennas"

Alkhalifeh, Khaldoun ; Ozdemir, Nilufer Aslihan ; Craeye, Christophe

Abstract

A novel technique is presented for the accurate and efficient simulation of Ground Penetrating Radar (GPR) antennas coupled to an arbitrary ground. The problem of generating an impedance matrix is reformulated using expressions of the basis and testing function far-field patterns which are independent of the ground's physical and electromagnetic parameters. This allows for efficient calculation of the antenna's impedance matrix while looping through values for the soil parameters

Document type : *Communication à un colloque (Conference Paper)*

Référence bibliographique

Alkhalifeh, Khaldoun ; Ozdemir, Nilufer Aslihan ; Craeye, Christophe. *Efficient Simulation of Coupled Ground Antennas.*9th European Conference on Antennas and Propagation (EUCAP) (Lisbon,Portugal., du 12/04/2015 au 17/04/2015).

Efficient Simulation of Coupled Ground Antennas

Khaldoun Alkhalifeh, Nilufer Ozdemir, Christophe Craeye
Université catholique de Louvain: ICTEAM Institute, Place du Levant, 2, 1348 Louvain-la-Neuve
$\{khaldoun.alkhalifeh, nilufer.ozdemir, christophe.craeye\}$@uclouvain.be,

***Abstract*—.**

A novel technique is presented for the accurate and efficient simulation of Ground Penetrating Radar (GPR) antennas coupled to an arbitrary ground. The problem of generating an impedance matrix is reformulated using expressions of the basis and testing function far-field patterns which are independent of the ground's physical and electromagnetic parameters. This allows for efficient calculation of the antenna's impedance matrix while looping through values for the soil parameters.

***Index Terms*—Method of Moments, contour deformation, Green's function.**

I. Introduction

Ground Penetrating Radars (GPR) are regularly used to investigate layered media [1]. This may involve estimating the complex permittivity, permeability and thicknesses of the ground's various layers [2]. Such characterization is often carried out by simulating the antenna(s) in use for a wide range of ground types (permittivity, number of layers, layer thicknesses etc.) and choosing the ground parameters that minimize the difference between antenna simulations and measurements [3]. This requires the same antenna to be simulated many times with a large number of prospective soil properties. This paper presents a novel solution of the Method of Moments (MoM) surface boundary problem for metal antennas above a planar ground [4]. The MoM matrix is first separated into a free space matrix and a ground reflection matrix. The ground reflection component is calculated as the product of basis and testing function far-field patterns with the ground's reflection coefficient. The off-line calculation of the free-space matrix and basis/testing function far-field patterns as well as the low computational cost of calculating the reflection coefficients and multiplying and summing the terms allows for efficient calculation of the antenna's MoM matrix, while changing the ground parameters. It is foreseen that this novel EM scattering solver will be of significant use to those interested in characterising grounds. The remainder of this paper presents the proposed algorithm mathematically in Section II, and gives simulation results demonstrating efficient and accurate results in Section III. Conclusions are drawn in Section IV.

II. Mathematical formulation

A. TE and TM waves

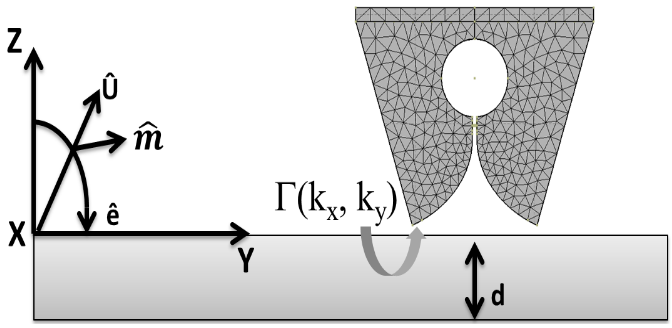

Fig. 1. Coordinates of reference with a single layer, antenna from [10]

We consider a reference radiator above a layered medium and excited by known electric and magnetic currents as illustrated in Fig. 1. As suggested in Fig. 2, each spectral component generates plane waves on both sides of plane $z = z_\circ$. On each side, TE and TM waves are generated. In general terms, those plane waves are defined as:

$$\vec{E} = \left(-\hat{m}\, A_{TE} + \hat{e}\, A_{TM}\right)\, e^{-jk_x x}\, e^{-jk_y y}\, e^{\pm jk_z z} \quad (1)$$
$$\vec{H} = \frac{1}{\eta}\, \left(\hat{e}\, A_{TE} + \hat{m}\, A_{TM}\right) e^{-jk_x x}\, e^{-jk_y y}\, e^{\pm jk_z z} \quad (2)$$

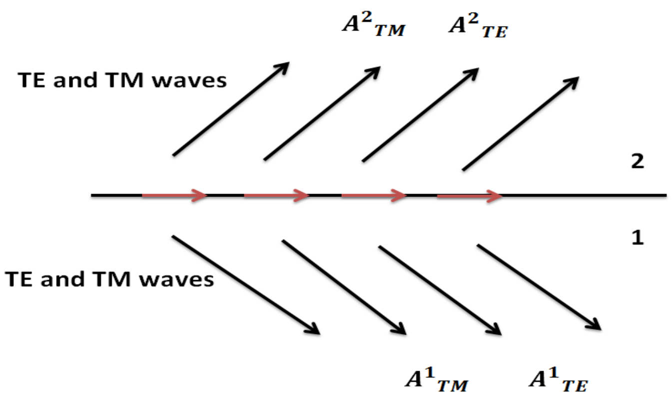

Fig. 2. Schematic representation of TE and TM waves radiated by a current sheet

For a given spectral component (k_x, k_y), with magnitude $\beta = \sqrt{k_x^2 + k_y^2}$, propagation occurs in direction

$\vec{k} = (k_x, k_y, k_z)$ with

$$k_x^2 + k_y^2 + k_z^2 = k^2 = \omega^2 \epsilon \mu \tag{3}$$

where ϵ and μ are the permittivity and permeability of the medium of propagation [5]. The normalized direction of propagation is $\hat{u} = \vec{k}/k$. In each medium, horizontal and vertical polarization vectors are defined by vectors perpendicular to the direction of propagation:

$$\hat{m} = \frac{1}{\beta} \begin{bmatrix} -k_y \\ k_x \\ 0 \end{bmatrix} \qquad \text{and} \qquad \hat{e} = \frac{1}{\beta\, k} \begin{bmatrix} k_x\, k_z \\ k_y\, k_z \\ -\beta^2 \end{bmatrix} \tag{4}$$

These expressions are provided for waves propagating upwards. For waves propagating downwards, $\hat{m}$ remains unchanged, while $\hat{e}$ has (only) its component along $\hat{z}$ changing sign [6].

B. Field reflected by the ground

Let us assume a Basis Function (BF) distributed over antenna 1, and a Testing Function (TF) distributed over antenna 2. The interaction Z_{21} between these BF and TF can be split into a free-space part and a ground-reflected part. The calculation of the latter will be accelerated here through a plane-wave spectrum approach with regular spacing [7] in (k_x, k_y) domain. This significantly reduces the computation time required to simulate GPR antennas. Let us denote by $\vec{J}_b$ the current distribution represented by the BF. The vector potential radiated in free-space by $\vec{J}_b$ can be written as:

$$\vec{A}(x,y,z) = \frac{1}{(2\,\pi)^2} \iiint_V \vec{J}_b(x',y',z') \iint \frac{e^{-j\,(k_x\,(x-x')+k_y\,(y-y')+k_z\,|z-z'|)}}{2\,j\,k_z}\, dk_x\, dk_y\, dV \tag{5}$$

The electric field propagating downwards ($z < z'$) with polarization p then becomes:

$$E_p(x,y,z) = \frac{-j\,k\,\eta}{(2\,\pi)^2} \iint F_{b,p}(k_x,k_y) \frac{e^{-j\,(k_x\,x+k_y\,y-k_z\,z)}}{2\,j\,k_z}\, dk_x\, dk_y \tag{6}$$

Where $F_{b,p}$ is the radiation pattern of the corresponding basis function. After reflection on ground, the field tested with a given testing function J_t then becomes:

$$E_p(x,y,z) = \frac{-j\,k\,\eta}{(2\,\pi)^2} \iint \Gamma(k_x,k_y) F_{t,p}(k_x,k_y) \frac{e^{-j\,(k_x\,x+k_y\,y-k_z\,z)}}{2\,j\,k_z}\, dk_x\, dk_y \tag{7}$$

where Γ is a reflection coefficient and $F_{t,p}$ is the pattern of the testing function. Regarding the patterns to be computed for each basis function, four different patterns will be needed. What distinguishes them is the polarization and direction (upward or downward) of propagation. Also, to include the reflection on the ground, one needs to calculate the reflection coefficients Γ_{TE} and Γ_{TM}. Finally, considering both polarizations, the total tested field becomes

$$Z^g = \frac{-j\,k\,\eta}{(2\,\pi)^2} \iint \left(F_{b,TE}\,F_{t,TE}\,\Gamma_{TE} + F_{b,TM}\,F_{t,TM}\,\Gamma_{TM}\right) \frac{1}{2\,j\,k_z}\, Q(k_x,k_y)\; dk_x\, dk_y \tag{8}$$

where Q is a factor [8] including the effect of contour deformation in complex wavenumber plane [9]. The final formulation can be written as a matrix product and the ground parameters may be efficiently changed. The precomputation of all entries allows a very fast integration.

Then, for all pairs of basis and testing functions, the MoM impedance matrix is given by:

$$Z = Z^g + Z^f \tag{9}$$

where Z^g includes the effect of the ground-medium Green's function. Z^f is the free-space impedance matrix.

III. Results and discussion

A. The case of a Vivaldi antenna

A Vivaldi antenna [10] with 7.5 by 10 cm dimensions is placed 0.5 cm from the ground as shown in Fig. 3. Validations for real and imaginary parts of the impedance in the presence of ground as a perfect electrical conductor are provided by comparing two methods: brute-force MoM with image and the proposed method. The proposed method requires 143.74 seconds of preparation time and only 0.076 seconds required to calculate the ground's contribution matrix Z^g while changing the ground characteristics at a single frequency. The proposed method allows for efficient loops over soil parameters. It is worth noting that it is not possible to loop over soil parameters using the brute-force method. The Vivaldi antenna is designed and meshed using GMSH [11]. An electromagnetic simulation software developed at UCL and based on the Method of Moments is used to calculate the free-space impedance (Z^f). Results are shown in Fig. 4, where a very good correspondence is obtained for this type of Vivaldi antenna with 1360 basis functions.

1) The effect k_x, k_y resolution: The spectral-domain MoM formulation for interaction between elementary basis functions considering the spectral samples k_x and k_y is given as [12]

$$Z_{tb} = \frac{1}{(2\,\pi)^2} \iint \left(\widetilde{H}(k_x,k_y) e^{-i(k_x\Delta x + k_y\Delta y)} dk_x dk_y \tag{10}\right.$$

$$\widetilde{H} = \widetilde{F}_t.\widetilde{G}.\widetilde{F_b^*} \tag{11}$$

Where $\widetilde{F}_t$, $\widetilde{F_b^*}$ are the Fourier transforms of elementary testing and basis functions, and $\widetilde{G}$ is the Dyadic form of

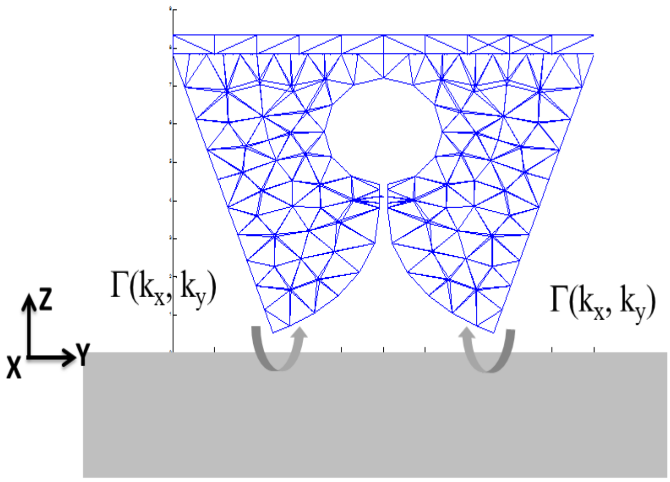

Fig. 3. Vivaldi antenna mesh in the presence of the ground

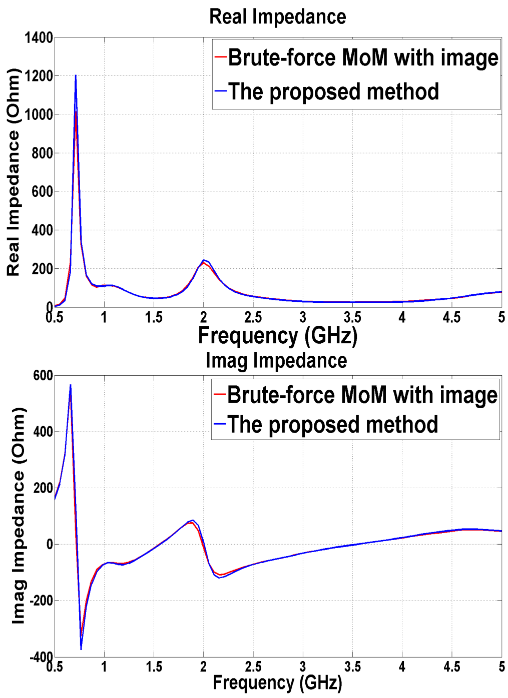

Fig. 4. Real and imaginary parts of the antenna-medium impedance for the Vivaldi antenna

the layered medium Green's function. In using the spectral-domain, the appropriate choice of k_x,k_y is very important. A coarse grid of k_x,k_y will not represent properly the "Sinc" functions obtained from Fourier transform of two rectangle basis functions in space-domain. On the other hand, a fine grid of k_x,k_y will increase the computational issues related to the matrix filling time. Fig. 5 shows the effect of k_x,k_y resolution for the Vivaldi antenna mentioned above in the presence of ground as a perfect electrical conductor. The simulation results for three different k_x, k_y grids show that by using a finer k_x, k_y gird, we approach the exact solution of brute-force MoM with image. The span between nk_x and nk_y values is taken the same for each grid.

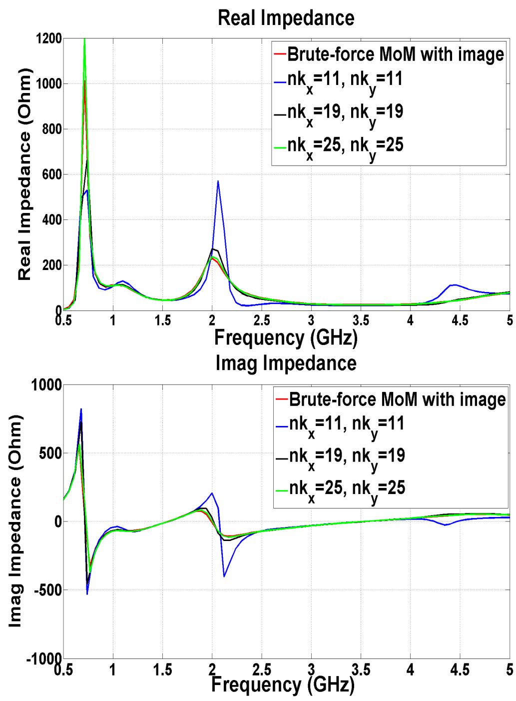

Fig. 5. The effect of k_x, k_y resolution, where nk_x and nk_y are the number of k_x and k_y values respectively

B. IE3D validation in the case of horizontal and vertical dipole

A single dipole with 5 by 0.25 cm has been chosen to validate the proposed method in the presence of ground with permittivity of ϵ_r. The horizontal dipole is placed 1 cm from an infinite ground with $\epsilon_r = 1000$ as shown in IE3D commercial software design [13] (Fig. 6). The comparison between IE3D simulation and the proposed method at the presence of lossy ground shows strong matching (Fig. 7). The same dipole is placed vertically 1 cm above the lossy ground to correspond the Vivaldi antenna scenario. The proposed method has the same level of good correspondence with IE3D simulation as shown in Fig. 8.

IV. Conclusion

A novel MoM surface boundary solution to the problem of metallic antennas above layered grounds has been presented. The technique allows for efficient calculation of the MoM matrix for cases where one wishes to loop through various values of ground permittivity, layer number, layer thicknesses, conductivities and/or permeability. Detailed simulations of three different GPR antenna types have demonstrated that the technique requires little computational time.

Acknowledgment

The authors would like to thank Dr. Greg Hislop, from CSIRO, Brisbane, Australia, for accelerating the calculation

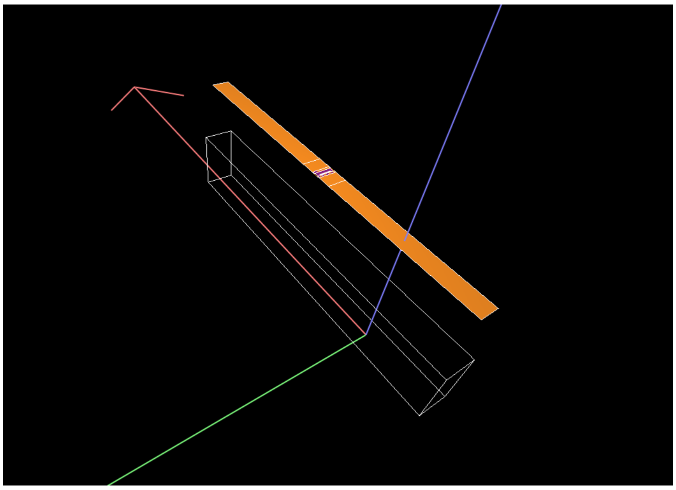

Fig. 6. Horizontal dipole in the presence of an infinite ground geometry

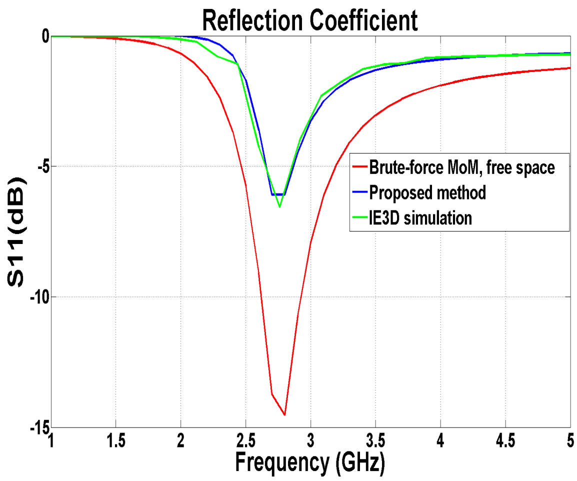

Fig. 7. Reflection coefficient comparison between the proposed method and IE3D, horizontal dipole case

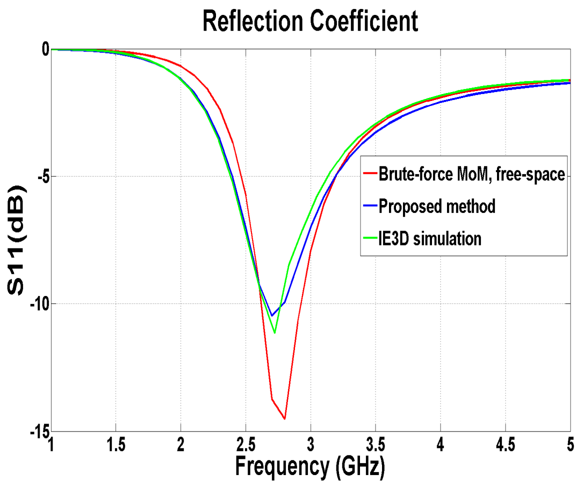

Fig. 8. Reflection coefficient comparison between the proposed method and IE3D, vertical dipole case

of matrix filling using a matrix product and for proof-reading the paper.

REFERENCES

[1] S. Lambot and F. André, *Full-wave modeling of near-field radar data for planar layered media reconstruction*, iGeoscience and Remote Sensing, IEEE Transactions on, vol. 52, no. 5, pp. 22952303, May 2014.

[2] G. Hislop, *Measuring the thickness, permittivity and conductivity of layered earth*, in Antennas and Propagation (EUCAP), Proceedings of the 8th European Conference on, Apr. 2014, pp. 43674370.

[3] A. Kalogeropoulos, J van der Kruk, J. Hugenschmidt, J. Bikowski, and E. Bruhwiler, *Full-waveform GPR inversion to assess chloride gradients in concrete*, NDT and E International, vol. 57, pp. 74 84, 2013.

[4] G. Hislop, S. Lambot, C. Craeye, D. Gonzalez-Ovejero, and R. Sarkis, *Antenna calibration for near-field problems with the method of moments*, in Antennas and Propagation (EUCAP), Proceedings of the 5th European Conference on, Apr. 2011, pp. 2004 2008.

[5] D. Pozar and D.H. Schaubert, *Microstrip Antennas: The analysis and design of microstrip antennas and arrays*, IEEE Trans. Antennas Propag., 1995.

[6] K.A. Michalski and J.R. Mosig, *Multilayered media Green's functions in integral equation formulations*, vol. 45, pp. 508-519, Mar. 1997.

[7] E. Martini, C. Craeye, N. Ozdemir and S. Maci, *Harmonics-based inhomogeneous plane-wave method (HIPW)*, submitted to IEEE Trans. Antennas propag., Jan. 2014.

[8] S.N Jha, C. Craeye, *Contour-FFT based spectral domain MBF analysis of large printed antenna arrays*, IEEE Trans. Antennas Propag., no.99, 2014.

[9] B. Hu, W.C. Chew, and S. Velamparambil, *Fast inhomogeneous plane wave algorithm for the analysis of electromagnetic scattering*, Radio Science, vol. 36, no. 6,pp. 1327-1340, 2001.

[10] K. Alkhalifeh, R. Sarkis and C. Craeye, *Wheel-of-Time array devoted to near-field imaging*, ICEAA13, September, 9-13- 2013, Torino, Italy.

[11] GMSH, *a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities. http://www.geuz.org/gmsh/.*

[12] T. Tiberi and W. Menzel, *A full-wave analysis method for open microstrip structures*, IEEE Trans. Antennas Propag., vol.29, no. 1, pp. 63-68, Jan. 1981.

[13] IE3D, Mentor Grapgics, http://www.mentor.com